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Organic Based Sorbents as Environmentally Friendly Solution for Industrial Waste Water

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Abstract
Over the past decade, organic-based sorbents derived from various plant and animal wastes have gained significant attention for their role in improving industrial wastewater treatment. This study provides a comprehensive review of the current applications of biomass in adsorbing hazardous pollutants, including heavy metals, dyes, oils and greases, antibiotics, and phenolic compounds, in both raw and synthetic industrial wastewater. The discussion focuses on plant- and animal-waste-derived sorbents, such as those obtained from tree bark, rice husks, fruit peels, and animal bones. Additionally, various modification techniques aimed at enhancing the performance of these biosorbents—such as carbonization, pyrolysis, and chemical treatments—are critically examined. In conclusion, the findings highlight that organic-based sorbents serve as a reliable, environmentally friendly alternative for mitigating aquatic pollution while also contributing to the growing trend of circular economy practices.

Keywords: Organic sorbent, Adsorption, plant and animal wastes, pollutants.

1. Introduction

Industrial wastewater is a significant environmental challenge, as it often contains hazardous pollutants from both detectable and undetectable sources, posing severe risks to environmental quality and public health [1, 2]. Unless proper treatment implemented, these contaminants can exacerbate the scarcity of clean water. Various industries, such as petroleum refining, petrochemical production, battery manufacturing, and textiles, contribute to wastewater laden with pollutants like heavy metals, dyes, phenolics, antibiotics, oil, and grease. This growing problem necessitates effective mitigation strategies, particularly as industrial activities expand globally [3].

The increasing industrial sectors has an avoidable impact including wastewater with high loading of pollutants like oil and grease, heavy metals, dyes, phenolic and antibiotic wastes. Multiple industrial sectors including petroleum and petrochemical industry, battery, plastics, textiles, cosmetics, and edible oil production have long been linked to polluted industrial water [4, 5]. To further solve this issue, industrial wastewater treatment including adsorption as it is considered

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as one of effective and efficient ways due to having relatively lower energy consumption, good efficiency, and environmentally safer [6,7].

To date, biosorbents made metal oxide, organic carbon and metal organic based materials have also been studied [2, 4, 8]. Furthermore, circular economic interest to recycle the used products has triggered more more effort to find and investigate other organic based materials [9]. While some relevant publications have reviewed the use of organic-based materials as sorbent for industrial wastewater, to the best of our knowledge and consideration, specific discussion on the usage of activated sorbent derived from plant and animal wastes for treating polluted water completed by comparative performance study is still needed. Therefore, this article aims to address this gap by reviewing recent advancements in the use of biomass-based sorbents for pollutant removal. Special attention is given to the application of sorbents derived from plant and animal waste for treating both simulated and real industrial wastewater. This comparative approach provides insights into their efficiency, cost-effectiveness, and sustainability, paving the way for more eco-friendly water treatment technologies.

2. Adsorption

Adsorption is acknowledged method having high efficiency, less energy and less chemicals consumption to do wastewater treatment process as it can accumulate pollutants on its surface, especially when it is activated before usage [4]. There are some aspects like pollutants and sorbent characteristics; pore diffusion, hydrogen bonding, electrostatic interaction, and van der walls forces, as well as right operating conditions which affect adsorption efficiency [10,11]. For increasing the adsorption forces, some activation like carbonization, and chemical activation may also be conducted prior to its contact to polluted aqueous solution [12-14].

The interaction process between the sorbent and contaminants is influenced by the sorbent' saffinity, which continues until equilibrium is reached. To understand this interaction quantitatively, the batch equilibrium isotherm provides a crucial framework. Commonly applied isotherm models include the Langmuir and Freundlich models, which offer insights into the adsorption mechanisms. The Langmuir model posits that adsorption occurs on uniform sorbent surfaces with identical binding sites, while the Freundlich model suggests adsorption takes place on heterogeneous surfaces with varied site energies. The linearized equations of these models, detailed in Table 1, help describe these processes mathematically.

Table 1 Isotherm models

Isotherm Model	Linearized Formula		Definition
Freundlich	$\ln q_e = \ln k_f + \frac{1}{n}(\ln C_e)$	(1)	q_e: concentration of accumulated pollutant on sorbent at equilibrium time (mg/g) C_e: pollutant concentration at equilibrium (mg/L) k_f: isotherm constant n : adsorption intensity q_m: maximum adsorption capacity (mg/g).
Langmuir	$\frac{C_e}{q_e} = \left(\frac{1}{K_l\, q_m}\right) + \frac{C_e}{q_m}$	(2)	

By forecasting the quantity of pollutants adsorbed in terms of time parameters, in addition to external mass transfer and solute diffusivity, adsorption kinetic analysis can aid in the comprehension of the adsorption process design. To depict the most likely mechanisms that occur during the adsorption process, such as pseudo-first order, pseudo-second order, and intra-particle diffusion, kinetic models have been used extensively and compared to one another. Their linearized formulas are given in Eqs. 3-5, respectively (Table 2).

Table 2 Adsorption kinetics

Adsorption Kinetics	Linearized Formula		Definition
Pseudo-first order	$\log(q_e - q_t) = \log(q_e) - \frac{K_1}{2.303}.t$	(3)	q_t: Binded pollutants on sorbent surface (mg/g) K_1: The equilibrium rate constant (min^{-1})
Pseudo-second order	$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{1}{q_e}.t$	(4)	t : Contact time (min)
Intra-particle diffusion	$q_t = K_{id}\, t^{0.5}$	(5)	k_2: Order rate constant (g/mg min) K_{id}: The rate constant, intra-particle diffusion (mg/g.min$^{0.5}$) $t^{0.5}$: The square root of time

The pseudo-second order model suggests the term of reciprocal action between sorbent sites and pollutant particles that may occur as a result of the adsorption process, whereas the pseudo-first-order model can be thought of as the rate of residence of sites in the adsorbent due to the adsorption process regarding the proportionate rate to the void site. Conversely, the pseudo-second order model suggests the notion of reciprocal action between pollutant particles and sorbent sites, which could occur as a result of their strong binding, which is confirmed by the chemisorption process [15, 16]. Furthermore, intra-particle diffusion presented an alternative

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theory, stating that pollutant uptakes might be more likely to fluctuate proportionately with t½ as opposed to contact time [17].

3. Sorbent Derived From Plant Mass

There is growing interest in plant-based sorbent research for a number of reasons. Recycling a variety of plant wastes may be one way to find green ways to address environmental problems associated with agricultural waste [18, 19]. In addition to this factor, the need to discover more affordable and ecologically friendly sorbent materials has prompted increased efforts to expand the use of green sorbents [20]. Numerous plant remnants, including bark or wood, vegetable leftovers, fruit peel and seed, and plant leaves, have been shown to be dependable sorbents thus far.

3.1 Tree Bark Waste

Remains of bark and wood are part of renewable sorbent materials that are found in abundance in nature [21]. As a result, this material's availability has made it possible to create efficient and environmentally friendly sorbents.

Eucalyptus trees can grow greatly throughout several years, particularly in some countries like Australia and New Zealand. The woody waste of this plant is mostly left useless at the ground, therefore a few studies then utilized it due to its potential as organic sorbent material. A file on eucalyptus bark (EB) performance in treating raw petroleum refinery wastewater concluded that the modified EB becomes extra powerful to simultaneously cast off COD, oil, and Cr(III) from the effluent than its raw version [22]. The comparative evaluation which includes chemically impregnated EB, carbonized EB, and hybrid activated EB found that a hybrid chemical and thermal activation would increase sorbent efficacy. Another study deployed EB primarily based sorbent for Cu(II) metallic ions omission from uncooked gold mining wastewater and stated pleasant final results [23]. in this examination, uncooked powder EB installed wastewater with excessive metal content ought to bring about maximum elimination performance of Cu (II) by using round 92 % at pH five after ninety min. [24]. Its efficacy is probably attributed to several practical businesses at the sorbent mass, including phenolic hydroxyl and methoxyl companies at the side of morphological heterogeneity.

Logwood can also be exploited as a sorbent to remove various pollutants including phenol compounds from aqueous media [25]. It was found that phosphoric acid and thermally activated logwood at the temperature of 500 °C for 60 min could form an amorphous sorbent having wide surface area, pore volume, and mean pore diameter by 181.49 m^2/g, 0.09396 cm^3/g, and 2.07 nm, respectively, and be able to adsorb of 94.09 mg/g of phenol compounds.

Regarding pine bark material, a study informed that quaternary ammonium-modified pinebark could be employed as a sorbent for adsorbing vanadium [26]. This study revealed that the initial sodium hydroxide concentration was a determining factor. However, another study proposed that initial modification on organic sorbent made of pine bark sorbent using hydrochloric acid and sodium hydroxide solutions for Cu(II) ions adsorption showed lower uptake than its unmodified version [27].

3.2 Fruit Waste

The potentiality of banana waste as a sorbent material has been reported in current studies to be able to be utilized in removing organic and inorganic pollutants from polluted solution. Research show Methylene blue dye concentration in raw textile wastewater could be reduced by more than 86.88% using only 0.4 g of banana peel-derived sorbent [18]. This was followed by other studies that created a banana peel-based biochar/iron oxide composite to adsorb Methylene blue dye. At an initial dye concentration of 500 mg/L in near-neutral pH and standard temperature, it managed to experience a great adsorption capacity of 862 mg/g [28]. Furthermore, its following study also suggests that this sorbent is economically dependable due to its relatively consistent performance even after five repeated cycles.

Another popular fruit with major peel disposal is watermelon, where its waste is used and investigated in a thallium(I) adsorption study [29]. Through iron exchange mechanism, the watermelon peel-based biochar was capable of reaching 178.4 mg/g of thallium(I) adsorption capacity. Furthermore, metal ions – specifically As(V) and (II), could also be eliminated using the watermelon-based sorbent [30]. The comparison study involved raw, xanthate and citric acid-modified melon rind based sorbents showed that xanthate-modified water melon rind has greater As(V) and As(III) removal efficiency than the investigated alternatives. Compared to its raw version, xanthated watermelon rind has a higher adsorption rate by up to 49% for both metal ions. Moreover, watermelon rind activated through ZnS nanoparticles for the adsorption of various heavy metals like Pb(II), Cd(II), Cu(II), Ni(II) and Co(II), are also reported capable as adsorbent [31].

3.3 Rice Husk Waste

Reports have shown the potentiality of rice husk as a sorbent material for the removal of different pollutants. The major chemical components of this biomass, such as cellulose, hemicellulose, lignin, and other organic matter, have proven to be favorable in supporting adsorption aims. For example, rice husk-based sorbents are capable of removing recalcitrant pollutants like phenol [32]. Rice husk treated by thermal activation have displayed higher surface area, allowing greater phenol removal efficiency relative to particular functional groups including OH, C-C, C = C, C≡C, C-O. Moreover, compared to rice husk sorbents treated by salts and surfactant impregnation, rice husk valorized through HCl impregnation for adsorbing various dyes, specifically direct orange-26, direct red-31, direct blue-67 and direct orange-3GL, has been reported to be more capable [33]. In addition, rice husk-based biochar synthesized through one and two-step KOH-catalyzed pyrolysis also displayed a favorable result in another study [34]. Biochar with two-step pyrolysis showed better outcome than the other methods, where the increase in the mass ratio of KOH and char led to a decrease in the sorbent yield. Thus, the activation process had a great influence on the surface area and carbon porosity of the investigated sorbents. Biochar derived from the two-step pyrolysis were capable of reaching surface area of 2138m^2/g. Therefore, by following the Langmuir isotherm and pseudo-second-order kinetic model, this massive micro-porous structure was responsible for the high adsorption of phenol molecules, where it could achieve maximum adsorption capacity of 201 mg/g even in a few minutes of contact time.

3.4 Leaf Waste

Leaves, being a plant-based material, could also be used as a sorbent. Some studies have investigated the application of leaves waste, including the capabilities of *Platanus orientalis* leaves using mild hydrothermal carbonization and one-step calcination at a temperature of 750 °C [35]. This treated sorbent achieved a specific surface area of 1355.53 m^2/g, which is beneficial to remove dyes such as rhodamine B and methylene orange from solution. Another type of leaf, birch leaves (*Betula pendula*), activated by sulfuric acid for phenol adsorption also displayed competitive results by reaching a maximum adsorption capacity of 0.128 mmol/g [36]. This study also confirmed that the best temperature for phenol adsorption is between 35°C and 45°C for Langmuir's equation. As a result, sorbent derived from green neem leaves (*Azadirachta Indica*) used for phenol removal also tended to be effective as greater than 97.5% of the targeted pollutant was able to be removed despite the need for longer contact time (4 h) [37]. Furthermore, desorption study through deploying ethanol-treatment revealed that the reusability of this material was only around half of its initial content. In addition, plant leaves such as aloe vera and mesquite leaves were also believed reliable as sorbent alternatives for the elimination of phenol, particularly at neutral pH [38].

4. Sorbent Derived From Animal Mass

As the global population increases exponentially over time, so too does the production and consumption of meat and other animal products worldwide. This has led to a greater generation of animal waste from agriculture, farms and other food related industries, reaching over millions of tons annually. The proper disposal of these wastes is crucial towards saving the environment and, simultaneously, supporting the circular economy system through recycling the waste materials. One method of fulfilling this is through the valorization of animal waste to be used as environmentally friendly sorbents. Studies reported that organic based sorbents derived from the bone of various animal like chicken, fish, bovine, cow, ostrich, and camel are an effective due to its composition of carbon and other favorable components to bind the pollutants.

4.1 Animal Bone waste

Currently, valorized chicken bone as a natural sorbent has been shown to cover a wide range of pollutant types and activation modes. To begin with, biochar based of chicken bone treated at lower carbonization temperatures demonstrated how its polar function group is beneficial in adsorbing metal Cr(VI) ion [39]. Further examination shows this biochar could also absorb metal lead ions by conducting pyrolysis on different parts of the chicken bone [40]. Post conducting of this comparative analysis, this study showed that the chicken tibia bone-based biochar outperformed the pelvat, ribs, clavicle, vertebrae, and numerus bone-based biochars. After this, its regeneration rate was also investigated, where it was revealed that the metal ions trapped on the sorbent surface were mostly able to be desorbed using an acid solution – confirming its dependable regeneration rate. In addition, the next study developed an interesting chicken bone with double coating through iron and magnesium hydroxides and claimed that this could allow the cadmium metal ions contained in the solution to be mostly reduced [41].

As fish waste contributes to a major component of animal waste, fish bone has great potentiality as a natural sorbent especially with its competitive efficacy compared to other organic materials. In a recent study, the performance of bone bio char from pleco fish (*Pterygoplichthys spp*.) was shown to be promising in both fluoride and Cd(II) metal ion removal [42]. With a surface area of around $110m^2/g$, it provided better results for the removal of fluoride at a lower pH and Cd(II) at a higher pH. In addition, electrostatic attractions, ion exchange, and physisorption was reported to have occurred in the adsorption process through a deeper characterization analysis. Due to the complexity of the solution in nature, the implementation of this sorbent in the treatment of synthetic and raw aqueous media may have some differences: for instance, raw wastewater from abattoirs. A study considered this issue through utilizing fish bone chito-protein as both sorbent and coagulant agent for reducing particle load [43]. As a result, it was shown that most of the particle load were able to be reduced alongside the BOD concentration.

Therefore, the bone synthesis of other fish species, specifically Catla fish, was also proven to be dependable by successfully eliminating approximately 77% of crystal violet and 87% of Congo red dyes within 75 minutes, alongside the addition of photocatalytic treatment [44].

Relevant studies have taken note of the usage of bovine bone as a sorbent base. To begin, a bovine bone-based sorbent activated through the impregnation of NaOH was shown to be effective in extracting chromium ions from raw chrome electroplating wastewater [45]. This is because biosorbent modified by chemical impregnation using NaOH could have multiple increase in its adsorption capacity due to more active surface area on the adsorbent surface.

Cow farms are commonly considered to hold a majority of the global meat industry, producing vast amounts of cow bone waste. As a result, cow bone is readily available for organic sorbent production. A study produced nitrogenous biochar from this bone using a ball-milling technique, and it reported that this breakthrough was successful in the reduction of heavy metals [16]. Furthermore, another study found that cow bone-based sorbent could be a suitable alternative for purifying raw cassava wastewater due to its potentiality to reach a high adsorption ability for removing many heavy metals with at least 0.02 g of this sorbent dose [46]. The above-mentioned result was highly competitive in comparison to any other commercial sorbents available.

Ostrich bone-based sorbent was also found to be highly effective in capturing pollutants. For example, heavy metal lead ions could be removed from aqueous solutions after only 5 minutes of

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contact with the sorbent [47]. Other study improved the nature of ostrich bone as a unique composite ash/nanoscale zerovalent iron for adsorbing Hg(II) and Pb(II) metal ions in a fixed-bed column manner [48]. However, the efficacy of this modified ostrich bone was not identical to all types of metal ions, as Hg(II) and Pb(II) had a higher removal efficiency as compared to Ni(II) and Cd(II). Both fresh and used sorbent were viewed as economically viable due to the relative stability of sorbent performance even after repeated adsorption cycle [49].

Due to the increasing demand in the meat industry, tourism and traditional transportation in areas such as the Mediterranean countries, the population of camels globally has been increasing. This has subsequently led to the issue of an increasing number of camel carcasses. Using them as sorbent material may be part of an environmentally friendly solution to control both solid waste and industrial wastewater treatment. Some studies have revealed the ability of this low-cost material to adsorb various contaminants, particularly heavy metal ions. Camel bone-based sorbents for Cd(II) and Pb(II) ion removal, for example, were well documented in this field [50]. Other research then developed magnetic composite sorbent derived from camel bones through chemically treating the sorbent surface with Fe3O4. [51]. The presence of Ca, P, and C on the modified sorbent increased its sorption capacity, reaching 315 mg/g for Pb(II), 300.8 mg/g for Cd(II), and 271.7 mg/g for Co(II), consecutively. This could be caused by the characteristics of chemically modified sorbent (Fe_3O_4) which has specific affinity related to the ions of certain heavy metals such as Ca, P, and C leading to better adsorption capacity.

4.2 Other Animal Waste

Other than the bones explored above, animal wastes can also be in the forms of feathers or fur, beaks, hooves, or excretion, like dung. This has led to an increasing interest in the exploration of those wastes and their sorption potentiality, resulting in an increasing number of studies investigating these various animal remains. To begin with, hazardous Cr(VI) metal ions were successfully removed from solutions using chicken feathers [52]. This sorbent could attain high monolayer capacity at extremely acidic pH. When the feathers were acidified with nitric acid, the adsorption capacity of Cr(VI) ions in fixed bed mode was shown to be more desirable [53]. However, this study discovered that other types of metal ions, such as Cu(II), Mn(II), and Co(II), could not be as efficiently adsorbed. Thus, this phenomenon requires additional investigation because it could be attributed to specific metal qualities behaving differently against initial behavior of the sorbent. Furthermore, the defluorination procedure was carried out in the batch mode using chemically activated chicken feathers [54]. When the sorbent dosage was increased eightfold, the experimental data showed that the fluoride elimination increased by a factor of two. Another study compared the development of sorbent obtained from chicken femur, chicken beak, and fishbone wastes via carbonisation at 900ºC to adsorb Cd(II) metal ions from raw shipbuilding wastewater [55]. It found that sorbents made from chicken femurs outperformed those derived from chicken beaks and fishbones. Furthermore, unlike prior studies that found acidic pH to be beneficial, this study discovered that a near neutral pH of 6 was optimal for removing specific metal ions from the solution employed.

Following with the comparative examination of plant and animal wastes, a study provided an intriguing analysis dealing with a hydrothermal liquefaction technique to individually activate rice husk and cow dung under the same operating circumstances for dye removal. It then claimed that the remaining Congo red dye in raw textile effluent could be reduced by up to 96.9% and 98.8% utilizing rice husk and cow dung-based sorbents respectively [56]. From this perspective, it is clear that plant and animal waste are trustworthy source and has comparative capability to commercial sorbents in terms of adsorbing various contaminants from aqueous media.

Conclusions

The increasing expansion of multiple industries has serious impact on the amount of polluted aquatic medium. This issue needs proper solution to avoid further negative effects on human health and the environment. To answer this challenge, green technology should be prioritised for controlling wastewater issues and solid waste in the initial stage. This review addressed on current utilization of organic waste derived from plant and animal remains as sorbent materials to treat polluted solution. In other word, relevant research publications have been comprehensively discussed along with the characteristics and sorbents performance. Parts of plant like bark, leaves, husk, and peels as well as animal wastes like bone and fur have also been reported as dependable sorbent to adsorb various pollutants contained in both synthetic and raw wastewaters. To conclude, it is predicted that the exploration and utilization of biomass as sorbent material will be increasing in the near future due to the increasing awareness of keeping the quality of environment and the interest of modern society in applying circular economy system.

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